A Two-Stage Scheduling Optimization Model and Corresponding Solving Algorithm for Power Grid Containing Wind Farm and Energy Storage System Considering Demand Response

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Abstract. In allusion to the effects on system stability brought by wind power uncertainty, the energy storage system and demand response are led into the optimal dispatching of power grid containing wind farms. Firstly, the interval method is utilized to simulate the scene of wind farm and a Kantorovich distance based scene cut strategy is constructed; secondly, the demand response and energy storage system are led into the demand side and generation side respectively; thirdly, combining with two-stage optimization theory and taking the day-ahead predicted wind power and ultra-short term predicted wind power as random variable and its implementation a two-stage scheduling optimization model for wind farm and energy storage system, in which the demand response is taken into account, is constructed. To solve the constructed model, the chaos searching is led into traditional binary particle swarm optimization (PSO) algorithm to a construct chaotic binary PSO algorithm; finally, the simulation based on IEEE 36-bus 10-machine system, to which a wind farm with capacity of 650 MW is connected, is performed. Simulation results show that the global optimal solution can be obtained by chaotic binary PSO algorithm, thus this algorithm is suitable to solve the two-stage scheduling optimization model for wind farm and energy storage system; utilizing the synergetic effect of demand response with energy storage system the uncertainty of wind power can be suppressed and the wind energy utilization efficiency can be improved, meanwhile the coal consumption for grid power generation can be reduced, so the comprehensive benefits of the proposed strategy are obvious.

Introduction

The integration of large-scale wind power needs to be supported by the collaboration of the generation side and the user side. At the generation side, the high quality power for the reserve service shall be selected for the coordination with the power generation dispatching of the system, while the environmental capacity and the characteristics of resource distribution make the energy storage system gradually become the preferred backup service[1]. At the user side, implement the demand response, guide the user to use the power in a rational way, shift the time of power use, optimize the distribution of load demand[2]. The conduct of the research on the wind energy storage system combined with the optimized dispatch under the participation of demand response is advantageous for the improvement of the absorptive capacity of the wind power system.

With the regard to the research on the problem of wind power energy storage system combined with the optimized dispatch under the demand response, the current research can be classified as 3 aspects which are the analysis on the uncertainty of the wind power, the establishment of the schedule model and the structure of the solution algorithm. With the regard to the establishment of the schedule model, the uncertainty of wind power is not considered.

In summary, this article builds the model and the solution algorithm of wind power energy storage combined with the optimized dispatch with the consideration of the demand response. Firstly, consider the current predicted results of wind power and the super short term predicted results of wind
power as the change variable and its effectuation, establish the model of optimized dispatch for the wind power energy storage system at the two stages of day ahead and hour ahead; and then suggest the chaotic binary particle swarm optimization algorithm, CBPSO since the application of the improved binary particle swarm optimization algorithm for the periodicity of the chaotic search will fall into the defect of local optimum. At last, with the system of 10 machine at the IEEE 36 joint as the simulation system, analyze the improved effect of the demand response and the energy storage system on the capability of the system for the assimilation of the wind power.

The Model of Two-Phase Scheduling Optimization for Wind Power Energy Storage

The Current Scheduling Model

With the target of the expected value for the cost of power generation by the system being the minimum, make the arrangement for the machine groups of the system at the day ahead, the object function is as follows:

\[ \min E = \sum_{i=1}^{I} \sum_{h=1}^{H} p_h (C_{i,h} + C_{i,h}^{stg} + C_{i,h}^{DR}) \]

In the equation, \( E \) is the expected cost for the scheduling model of the system at the current time; \( I \) is the number of groups for the fire motors; \( H \) is the number of scenes; \( p_h \) is the probability for the output scene of the wind power field \( h \); \( C_{i,h} \), \( C_{i,h}^{stg} \) are the cost of coal burning and the cost of start and stop for the power generation of by the fire motor groups respectively; \( C_{i,h}^{DR} \) is the cost for the grid connection of the energy storage system; \( C_{i,h}^{DR} \) is the cost for the demand response of the system.

\[ C_{i,h} = \alpha_i + \beta_i g_i + \gamma_i (g_i)^2 \]  

\[ C_{i,h}^{stg} = [u_{i,h} (1 - u_{i,h-1})] N_{i,h} \]

In the equation: \( \alpha_i, \beta_i, \gamma_i \) are the coefficient of fuel cost for the generating units \( i \); \( g_i \) is the power generation volume of the fire motor group \( i \); \( u_{i,h} \) is the status of start and stop for the fire motor group; \( N_{i,h} \) is the cost for the start and stop of the machine group.

\[ C_{i,h}^{DR} = -\frac{1}{b} (\Delta L_i)^2 + \frac{L_0^0 - a}{b} (\Delta L_i) \]

In the equation: \( a \) and \( b \) are the coefficient of the linear function for the demand and price; \( \Delta L_i \) indicates the amount of reduction for the load after the introduction of demand response; \( L_0^0 \) is the load before the introduction of demand response.

The energy storage system will generate for the power consumption of itself during the charge and discharge, the calculation for the cost of power loss of the energy storage system at the time of \( t \) is as follows:

\[ C_{t}^{stg} = \frac{1}{N_{t,s}} (\Delta g_{stg}^c + \Delta g_{stg}^d) \]

In the equation: \( N_{t,s} \) is the number of system for th energy storage; \( B_{s,t} \) is the cost of getting online for the energy storage system \( s \) at the time of \( t \); \( g_{stg}^c \) and \( g_{stg}^d \) are the power rate of charge and discharge for the energy storage system.

The constraint condition of the scheduling model of day ahead is as follows:

1) The constraint for the balance of load.
\[
\sum_{j=1}^{I} g_{j, w} (1 - \psi_i) + \sum_{s=1}^{S} g_{s, \tau} (1 - \rho_s^c) + \sum_{w=1}^{W} g_{w, \tau} (1 - \varphi) = L_0 - \Delta L + \sum_{s=1}^{S} g_{s, \tau} (1 + \rho_s^d)
\]  

(5)

In the equation: \( W \) is the total number for the machine group of wind power; \( \psi_i \) is the power consumption rate of the machine group \( i \) for the use of the plant; \( \rho_s^c \), \( \rho_s^d \) are the rate of power loss during the charge and discharge for the electric automobile; \( \varphi \) is the power rate for the use of the field at the wind power field \( w \).

2) The constraint for the power rate of the energy storage system.

The main conditions of constraint for the energy storage system include the constraint for the power rate during the charge and discharge, the constraint for the status of charge and discharge and the constraint for the capacity of energy storage by the battery etc.

3) The constraint for the output of the fire motor group.

The participation of the fire motor group to the scheduling is mainly subject to the constraint of output, the constraint of climbing and the constraint of time for the start and stop.

4) The constraint of response at the demand side.

The demand response forms the simulated machine group of power generation by changing the users' method of power consumption, improving the efficiency of power consumption at the terminals, reducing the power consumption at the terminals for the participation of the system scheduling.

\[
0 \leq \Delta L \leq \Delta L_{\text{max}} \quad \text{v}_i
\]  

(7)

In the equation, \( v_i \) is the variable of 0-1, it indicates the reduction of load when \( v_i = 1 \), it indicates the load is not reduced at the other time; \( \Delta L_{\text{max}} \) indicates the maximum amount for the reduction of the load at the time of \( t \).

\[
0 \leq \Delta L_t - \Delta L_{t-1} \leq L_u
\]  

(8)

\[
0 \leq \Delta L_{t-1} - \Delta L_t \leq L_d
\]  

(9)

In the equation: \( L_u \) and \( L_d \) are the upper and lower limit of climb for the reduction of load under the demand response respectively. The demand response needs to meet the constraint of the start and stop time, otherwise it will cause the increase of curve volatility of the load.

\[
[X_{\text{on}}^m - T_u] (v_{t-1} - v_t) \geq 0
\]  

(10)

\[
[X_{\text{off}}^m - T_d] (v_t - v_{t-1}) \geq 0
\]  

(11)

In the equation: \( X_{\text{on}}^m \), \( X_{\text{off}}^m \) are the constraints for the start and stop time of the load; \( T_u \) and \( T_d \) are the minimum time of start and stop for the load. The reduction amount of the load during the whole scheduling period should be lower than the total reduction amount of the load.

\[
\sum_{t=1}^{T} (L_t^\text{max} - \Delta L_t) \leq M^\text{max}
\]  

(12)

In the equation: \( L_t^\text{max} \) indicates the maximum load at the time of \( t \); \( M^\text{max} \) is the maximum load.

The Current Scheduling Model

During the scheduling period of hour ahead, the correction for the system on the scheduling plan of day ahead in accordance with the predicted result of super short term for the wind power rate requires 2 steps: correct the operation mode of the energy storage system with the target of the net load of the
system being the minimum; correct the output of the fire motor group to form the scheduling method of hour ahead for the machine group on the base of the combination of the fire motor groups of hour ahead with the target of the power generation cost being the minimum.

1) The model of correction for the output of the energy storage system.
Correct the output of the energy storage system with the target of the net load of the system being the minimum, the object function is as follows:

$$
\min D' = -\sum_{s} g_{s,t} - \sum_{w} g_{w,t} + \sum_{s} g_{s,t}^* + \sum_{w} g_{w,t}^* \]
(13)

In the equation: $g_{w,t}'$ is the predicted result for the wind power in a super short term at the time of t on the current day, $g_{s,t}, g_{s,t}'$ are the output of the energy storage system at the time of t before and after the correction; $D'$ is the fluctuation of wind power at the stage of hour ahead.

2) The model for the correction of the output by the fire motor group.
Correct the output for the operation of the fire motor group that has already been initiated with the target of the cost of coal consumption $E'$ for the generation of power being the minimum, the specific object function is as follows:

$$
\min E' = \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{h=1}^{H} p_{h} C_{i,h}^\prime \]
(14)

In the equation, $C_{i,h}^\prime$ indicates the cost of coal consumption for the power generation of the system during the period of hour ahead.

After the correction, the output of the fire motor group is required to meet the following conditions of constraint:

$$
\sum_{i=1}^{I} g_{s,i}^*(1-\psi_i) + \sum_{i=1}^{S} g_{s,i}^* + \sum_{w=1}^{W} g_{w,t}^* (1-\varphi_w) =
L_t - \Delta L_t + \sum_{s=1}^{S} g_{s,t}^* \]
(15)

In the equation: $g_{s,i}^*$ indicates the corrected output of the machine group i at the time of t; $g_{w,t}^*$ and $g_{s,i}^*$

Indicate the corrected output of the energy storage system during the period of hour ahead respectively; $L_t$ is the load at the time of t; $u_{i,t}$ is the known quantity that has been determined during the period of day ahead.

The machine group of power generation and the generation system during this period still need to meet the related conditions of constraint during the period of day ahead.

Chaotic Binary Particle Swarm Optimization Algorithm

Apply the chaotic binary particle swarm optimization algorithm for the solution of the scheduling optimization model at the two stages of wind power and energy storage, need to conduct the coding for the status of output by the fire motor group and the energy storage system. Apply the algorithm of CBPSO for the solution of the model, the steps are as follows:

1) Implement the binary particle swarm optimization algorithm for the system, update the position and speed of the particles.

2) Calculate for the distance between any particle and the optimal particle swarm optimization in step 1), set $k_i$ as any particle at the current position of i, $k_r$ as the current position of the optimal particle, then the distance between the two particles is

$$
d_i = (k_i - k_r)^2 \]
(16)
If \( d_i \) is less than the pre-set value (this article takes \( 10^{-3} \)), then conduct the chaotic search for \( k_i \), get the new particles within the steps specified in the regulations as the substitute for the original particle until the final particle group is formed.

3) Judge whether the status of the final particles meet the various kinds of constraint conditions, keep it if it meets the conditions, take the limit value if it does not meet the conditions.

4) Calculate for the adaptive value of the respective particles in the final particle swarm optimization, and get global optimum \( F_{best} \), the global optimal position \( K \) and the individual optimal position \( k_{i, best} \), switch to step 5).

5) Judge whether the current number of iterations reaches the maximum value, if it reaches the maximum value, then output the result, otherwise the number of iterations should be set as \( n_i = n_i + 1 \) and switch to step 1.

The Analysis on the Example

The Setting for the Simulated Scenes

Set 4 kinds of simulated scenes for the system, analyze the impact of the energy storage system and the demand response on the capability of the system for the absorption of wind power;

Case1: the basic scene, this scene cannot be introduced with the energy storage system and the demand response.

Case2: the energy storage scene, this scene can only be introduced with the energy storage system, set the capacity of the energy storage system as 200MW, the maximum power rate for the charge and discharge is 80MW, the power loss for the charge and discharge is 0.04, the initial energy storage is 0.

Case3: the demand response scene, this scene can only be introduced with demand response, and the setting for the maximum reduction amount of the load should not be over 25% of the demand for the original load, the volatility for the reduction of load should not be over 100MW.

Case4: the comprehensive scene, this scene can be introduced with both the demand response and the energy storage system, the specific parameters are the same as those in Case 2 and Case 3.

The Comparison for the Results of the 4 Scenes

Looking at the overall system energy efficiency levels, the introduction of energy storage system and the demand response effectively reduces the total amount of power generation and the average coal consumption for the power generation with better economic benefits. The cost for the power generation of the system under the 4 scenes are the standard coal of 11 983t, 11 901t, 10 052t, 9 832.6t respectively, the cost for the start and stop are the standard coal of 145.8 t, 128 t, 122 t, 95.4t. From the perspective of energy saving and emission reduction, the reduction of the total amount of coal consumption for the power generation and the average coal consumption for the power generation will also reduce the emission of greenhouse gases and polluting gases, the environmental benefit is apparent. Table 3 is the optimization method for the operation of the system in the 4 scenes.

Speaking of the demand for the load by the system alone, the introduction of energy storage system can transfer the demand of load at the peak period to the valley period, but it does not have the effect of reducing the total amount of the demand for the load, as it is indicated in Case1 and Case2; the introduction of demand response can reduce the total amount of demand for the load and the demand for the load at the peak period, but it does not have the effect of “filling the valley”, as it is indicated in Case3; the target of cutting the peak and filling the valley for the demand of load may be achieved by the introduction of both the energy storage system and the demand response. Image 3 is the system load demand curve in the 4 scenes.

Speaking of the output for the grid connection of wind power alone, when the energy storage system and the demand response are both introduced (Case4), the capability of the system for the absorption of wind power is the strongest, the abortion rate for the wind is reduced from 12% in Case1 to 5.06% in Case4; compared with Case2 and Case3, it can be discovered that the optimization effect is the same as it is for the output structure of the fire motor group, the output for the grid
connection of wind power in the scene with single introduction of demand response (Case3) will be better than that in the scene with single introduction of energy storage system (Case2). Image 4 is the status for the grid connection of wind power in the 4 scenes.

Table 1. The system operation optimize results in four scenarios.

<table>
<thead>
<tr>
<th>Case</th>
<th>Load structure/%</th>
<th>load characteristic</th>
<th>Wind power</th>
<th>Thermal power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>valley time</td>
<td>normal time</td>
<td>peak time</td>
<td>Maxi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mum load</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>/MW</td>
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<td>h</td>
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<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>25.3</td>
<td>33.2</td>
<td>41.5</td>
<td>2700</td>
</tr>
<tr>
<td>2</td>
<td>25.5</td>
<td>33.3</td>
<td>41.2</td>
<td>2620</td>
</tr>
<tr>
<td>3</td>
<td>27.3</td>
<td>33.9</td>
<td>38.8</td>
<td>2350</td>
</tr>
<tr>
<td>4</td>
<td>27.4</td>
<td>34.0</td>
<td>38.5</td>
<td>2220</td>
</tr>
</tbody>
</table>

For the energy storage system, the period of charging for the energy storage system in Case 2 occurs at the valley period and the normal period, the total amount for the charge is 284.2 MW·h, the period of discharge only occurs at the peak period, Case 4 exists with the conduct of charge and discharge at the rest of the periods other than the peak period when it does not conduct the charging. Compared with Case1 and Case2, the introduction of energy storage system may reduce the standard coal for 105.8t.

The saving for the economic cost of the system is apparent; compared with Case2 and Case4, the amount of power for the grid connection in the energy storage system is more, it indicates that the energy storage system under the demand response can save more economic cost for the generation of power. Compared with Case 3 and Case4, it can be known that the introduction of energy saving system may improve the implementation effect of the demand response, table 4 is the running results of the energy storage system.

In summary, under the demand response, the introduction of energy storage system for the scheduling optimization of wind power energy storage with 2 stages can effectively reduce the level of power consumption for the power generation of the system, the environmental benefit and the economic benefit are significant.

Conclusion

The reverse distribution for the output of wind power and the time of demand for the load is the main reason for the wind power to abort large amount of wind. In order to enhance the grid connection of large scale for the wind power, it is required to introduce the demand response and the energy storage system to optimize the load distribution at the demand side. This article builds the wind power energy storage system with the combination of scheduling for the optimized model at the 2 stages and the chaotic binary particle swarm optimization algorithm, the result of the example indicates that:

1) The chaotic binary particle swarm optimization algorithm can utilize the ergodicity of chaotic search to conquer the insufficiency of the binary arithmetic that may fall into the local optimal solution, the algorithm has the applicability.

2) The model of scheduling optimization for the wind power energy storage at the stage 2 may
optimize the output structure of the fire motor group through the correction for the scheduling method of day ahead and reduce the cost for the power generation of the system and increase the capability of the system for the absorption of wind power.

3) The introduction of demand response and energy storage system may optimize the load distribution at the demand side, prevent the impact of uncertainty of the wind power on the capability of the system for the absorption of wind power. The optimization effect is optimal in the optimization result of Case4.

4) The improvement of the grid connection for the wind power requires the energy storage system as the reserve service, and with the premise of sacrificing the profit of power generation from the fire motor group, it is necessary to build the reasonable benefit distribution mechanism for the support of the energy storage system and the fire motor group.

References


